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NRL Memorandum Report 6295

Relativistic Focusing and Beat Wave Phase Velocity Control in the Plasma Beat Wave Accelerator

E. ESAREY AND A. TING

Berkeley Research Associates
P.O. Box 852
Springfield, VA 22150

P. SPRANGLE

Plasma Theory Branch
Plasma Physics Division

September 22, 1988

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No 0704-0188

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NRL Memorandum Report 6295	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Research Laboratory 6b OFFICE SYMBOL (If applicable) Code 4790	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Washington, DC 20375-5000	7b ADDRESS (City, State and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION U.S. Department of Energy 8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20545	10 SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO: DOE PROJECT NO: AI05-83 ER40117-A004 TASK NO: WORK UNIT ACCESSION NO:

11. TITLE (Include Security Classification)
Relativistic Focusing and Beat Wave Phase Velocity Control in the Plasma Beat Wave Accelerator

12. PERSONAL AUTHOR(S)
Esarey,* E., Ting,* A. and Sprangle, P.

13a. TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Interim	FROM ________ TO ______	1988 September 22	24

16 SUPPLEMENTARY NOTATION
*Berkeley Research Assoc., P.O. Box 852, Springfield, VA 22150

17. COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

Relativistic focusing allows two colinear short pulse radiation beams, provided they are of sufficiently high power, to propagate through a plasma without diffracting. By further accounting for finite radial beam geometry, it is possible for the phase velocity of the radiation beat (ponderomotive) wave to equal the speed of light. This removes one of the limiting factors, phase detuning between the accelerated electrons and the beat wave, in determining the maximum energy gain in the plasma beat wave accelerator.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a NAME OF RESPONSIBLE INDIVIDUAL P. Sprangle	22b TELEPHONE (Include Area Code) (202) 767-3493 22c OFFICE SYMBOL Code 4790

DD Form 1473, JUN 86 Previous editions are obsolete SECURITY CLASSIFICATION OF THIS PAGE

S/N 0102-LF-014-6603

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RELATIVISTIC FOCUSING AND BEAT WAVE PHASE VELOCITY CONTROL IN THE PLASMA BEAT WAVE ACCELERATOR

Introduction

Recently there has been much interest in plasma based accelerator schemes, such as the plasma beat wave accelerator (PBWA),[1-3] for producing ultra-high energy electrons. This has led to a renewed interest in the study of the propagation of intense radiation beams through a plasma.[4-13] In the PBWA two colinear radiation beams of frequencies ω_1, ω_2 are incident on a uniform plasma. By appropriately choosing the difference in the laser frequencies to be equal to the electron plasma frequency ω_p, $\Delta\omega = \omega_1 - \omega_2 = \omega_p$, where $\omega_p^2/\omega_1^2 << 1$, it is possible for the radiation beat wave to resonantly drive large amplitude electron plasma waves. In the ideal wave breaking limit,[14] the maximum accelerating electric field E_m is given by $E_m = (m_e c^2/e)\omega_p/c \simeq .97\sqrt{n_p}$ eV/cm where n_p is the plasma density in cm^{-3}. For example, $n_p = 1.6 \times 10^{16}$ cm^{-3} gives $E_m \simeq 120$ MeV/cm which implies that an electron could be accelerated to 1.2 TeV in 100 meters.

To realize such an acceleration scheme it is necessary that *i*) the radiation beams propagate at high intensity over distances large compared to the Rayleigh length $z_R = \omega r_s^2/2c$, where r_s is the radiation spot size, and that *ii*) phase resonance between the accelerating electrons and the plasma wave be maintained over an equally large distance. In vacuum, radiation diffracts over distances on the order of z_R, which can be relatively short. Hence, in order to maintain high intensity beams it is necessary to rely on focusing enhancement from the plasma. In the PBWA the phase velocity of the plasma wave is equal to the phase velocity of the radiation beat wave which, in the 1-D limit, is given by $v_p/c = \Delta\omega/\Delta k \simeq 1 - \omega_p^2/2\omega_1^2$, where $\Delta k = k_1 - k_2$ is the difference in the wave numbers of the two beams. Since the velocity of an ultra-relativistic electron is approximately the speed of light, the electrons out run the plasma wave and become "detuned" in a length[15] $L_d \simeq \lambda_p \omega_1^2/\omega_p^2$, where $\lambda_p = 2\pi c/\omega_p$. For $\omega_1/\omega_p = 25$ and $n_p = 1.6 \times 10^{16}$ cm^{-3}, this gives $L_d \simeq 16$ cm and a maximum electron energy gain of $\Delta\mathcal{E} \simeq E_m L_d \simeq 2$ GeV. In order to increase the energy gain beyond this detuning limit, it is necessary to increase the phase velocity of the plasma beat wave.

This paper addresses the two points mentioned above concerning the realization of the PBWA. As is shown below, matched beam solutions are possible in which the two radiation beams propagate with constant spot sizes provided the radiation is of sufficiently high power. This allows the radiation beams to propagate over distances larger than the Rayleigh length while maintaining their high intensities. For example, two radiation beams with equal spot sizes are matched provided the power in each beam is $P = P_c/3$.

Manuscript approved July 7, 1988.

where $P_c \simeq 17 \times 10^9 \omega^2/\omega_p^2$ W is the power threshold for relativistic focusing of a single radiation beam in a plasma.[4-8] In addition, by including finite radial beam profiles along with relativistic focusing, the phase velocity of the beat wave can be tuned to the speed of light. This is accomplished by appropriately choosing the initial spot sizes and powers of the radiation beams. Hence, phase resonance between the electron and beat wave can be maintained beyond the 1–D detuning length L_d and, consequently, substantially higher electron energies can be achieved. Figure 1 shows schematically the propagation of two matched radiation beams through a plasma with the resulting beat wave phase velocity equal to the speed of light.

Focusing of radiation beams in a plasma occurs through the combined effects of relativistic, ponderomotive and thermal self–focusing.[4-13] Typically these processes occur on widely separate time scales. Relativistic focusing[4-8] occurs on the shortest time scale, $\tau_R \sim 1/\omega$, which is the time scale at which the electrons respond to the radiation field. Ponderomotive focusing[9-11] depends on the expulsion of ions from the radiation channel and thus occurs on a time scale given roughly by $\tau_P \sim r_s/C_s$, where C_s is the ion acoustic speed. Thermal focusing[12,13] relies on heating of the plasma by the radiation beam and typically occurs on an even longer scale. This paper is concerned with relativistic focusing, and hence the analysis is applicable to lasers with pulse lengths τ_L in the range $\tau_R < \tau_L < \tau_P$, which is the region of interest for the PBWA. Physically, relativistic focusing arises solely from the relativistic electron quiver velocity, $v_q = ca_\perp/\gamma_\perp$, in the combined radiation field. Here $a_\perp = eA_\perp/mc^2$ is the normalized radiation vector potential and $\gamma_\perp = \sqrt{1 + a_\perp^2}$ is the relativistic gamma factor for an electron in a helically polarized radiation field. The focusing mechanism for a single beam is that a radiation profile peaked on axis leads to an index of refraction profile, $n \simeq 1 - (\omega_p/\omega)^2/2\gamma_\perp$, which has a minimum on axis. The radiation beam, therefore, focuses along the axis.[7] When the radiation power is greater than the critical power P_c for relativistic self–focusing, it is possible for the envelope of a single radiation beam to propagate at a constant spot size.[7] For two colinear beams, however, the situation is more complicated due to the coupling of one beam to the other through the relativistic gamma factor. The analysis presented below indicates that matched beam propagation for two beams is only possible for a finite range of the parameter R, such that $1/(\sqrt{8} - 1) < R < \sqrt{8} - 1$, where $R = (r_{s1}/r_{s2})^2$ is the square of the ratio of the spot sizes of the two beams. The radiation power required to obtain matched beam propagation for two beams is near that for a single beam, P_c.

Control of the beat wave phase velocity is most easily understood by the following heuristic argument. The finite radial extent of the radiation beams gives rise to a small

effective perpendicular wave number $k_\perp$. Here $k_\perp$ is a function not only of the spot size but also of the power due to the relativistic focusing effects. The existence of $k_\perp$ gives rise to an effective parallel wave number given by $k_\parallel \simeq (1 - \omega_p^2/2\omega^2 - c^2k_\perp^2/2\omega^2)\omega/c$. Hence, the parallel phase velocity of the beat wave is now given by $v_p/c \simeq 1 - \omega_p^2/2\omega^2 + (k_{\perp 1}^2 - k_{\perp 2}^2)c^2/2\omega\omega_p$. By appropriately choosing the initial spot sizes and powers of the two radiation beams, it is possible to have the last term in the expression for v_p/c cancel the second term thus providing $v_p = c$.

Analysis of Radiation Focusing and Beat Wave Phase Velocity Control

The analysis starts with the wave equation for the vector potential of the combined radiation field, $(\nabla^2 - c^{-2}\partial^2/\partial t^2)A_\perp = -(4\pi/c)J_\perp$, where $J_\perp$ is the transverse current density. In order to study the effects of relativistic focusing alone, only the current resulting from the electron quiver motion is needed, $J_\perp = -en_pv_q$. The wave equation is then given by

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)a_\perp = \frac{\omega_p^2}{c^2}a_\perp\left(1 + |a_1|^2 + |a_2|^2 + 2|a_1||a_2|\cos\Delta\Phi\right)^{-1/2}, \tag{1}$$

where $a_\perp = a_1 + a_2$. Throughout the following, a subscript 1 refers to the radiation beam of frequency ω_1, and a subscript 2 refers to the radiation beam of frequency ω_2. The factor within the square root is the relativistic gamma factor $\gamma_\perp$, assuming helically polarized radiation. Here, $\Delta\Phi = \Phi_1 - \Phi_2$ is the phase of the beat wave and $\Phi_{1,2} = k_{1,2}z - \omega_{1,2}t + \phi_{1,2}$, where $\phi_{1,2}$ is the slowly evolving phase of the radiation field.

In order to examine the qualitative diffractive properties of the radiation beams, it is helpful to consider the index of refraction $n_{1,2}$ of each beam. The approximate index of refraction associated with each beam is obtained in the following manner. First, the 1-D limit of the left hand side of Eq. (1) is taken, assuming $a \sim \exp(i\Phi)$. Next, Eq. (1) is divided by the phase factor $\exp(i\Phi)$ of either beam 1 or 2 and then averaged over a period of the beat phase $\Delta\Phi$. In the mildly relativistic limit $|a_{1,2}|^2 < 1$, the index of refraction for each beam is given by

$$n_1 = k_1c/\omega_1 = 1 - (\omega_p^2/2\omega_1^2)(1 - |a_1|^2/2 - |a_2|^2), \tag{2a}$$

$$n_2 = k_2c/\omega_2 = 1 - (\omega_p^2/2\omega_2^2)(1 - |a_1|^2 - |a_2|^2/2). \tag{2b}$$

In the above expressions, the first term (the unity) represents vacuum diffraction while the second term is the contribution from the ambient plasma. The remaining terms represent focusing from the radiation fields. More specifically, a term proportional to $(|a_1|^2 + |a_2|^2)/2$

results from the individual contributions of beam 1 and 2 to the relativistic factor $\gamma_\perp$, while the remaining term proportional to $|a_{1,2}|^2/2$ results from the contribution of the beat wave to $\gamma_\perp$. Radiation focusing occurs when $\partial n/\partial r < 0$. Hence, the contribution from the radiation terms to $n_{1,2}$ provide focusing for radiation profiles peaked on axis. For sufficiently high power, these focusing terms dominate the vacuum diffraction and provide overall focusing of the radiation beams.

Envelope equations describing the evolution of the spot size $r_s(z)$ of each beam are derived by applying the "source-dependent expansion" (SDE)[16,17] to Eq. (1). This is accomplished by expanding the normalized vector potential $a_{1,2}$ for each beam into a series of Gaussian-Laguerre polynomials and using orthogonality properties to determine their coefficients. The SDE differs from the typical vacuum modal expansion in that the parameters characterizing the Gaussian-Laguerre polynomials, such as the width of the Gaussian, are functions of z which depend on the "source", i.e. the right hand side of Eq. (1). Assuming that each beam is adequately described by the lowest order Gaussian mode $a = |a_{00}|\exp[i\beta - (1 - i\alpha)r^2/r_s^2]$, then the parameters $|a_{00}|$, β, α and r_s are given by $|a_{00}(z)| = a_0 r_{s0}/r_s(z)$, $\alpha(z) = (\omega/4c)dr_s^2/dz$ along with the following equations:

$$\frac{d^2}{dz^2}r_{s1} = \frac{4c^2}{\omega_1^2 r_{s1}^3}\left[1 - W_1\left(1 + \frac{8W_2R^2}{W_1(1+R)^2}\right)\right], \tag{3a}$$

$$\frac{d^2}{dz^2}r_{s2} = \frac{4c^2}{\omega_2^2 r_{s2}^3}\left[1 - W_2\left(1 + \frac{8W_1}{W_2(1+R)^2}\right)\right], \tag{3b}$$

$$\frac{d}{dz}\beta_1 = -\frac{2c}{\omega_1 r_{s1}^2}\left[1 + \frac{\omega_p^2 r_{s1}^2}{4c^2} - W_1\left(\frac{3}{2} + \frac{4W_2R(1+2R)}{W_1(1+R)^2}\right)\right], \tag{4a}$$

$$\frac{d}{dz}\beta_2 = -\frac{2c}{\omega_2 r_{s2}^2}\left[1 + \frac{\omega_p^2 r_{s2}^2}{4c^2} - W_2\left(\frac{3}{2} + \frac{4W_1(2+R)}{W_2(1+R)^2}\right)\right], \tag{4b}$$

where the mildly relativistic limit was taken, $|a_{1,2}|^2 < 1$. Physically, $W = (\omega_p a_0 r_{s0}/4c)^2 = P/P_c$ where P is the power in one of the beams and P_c is the critical power necessary for relativistic focusing of a single beam.[7] Here a_0 and r_{s0} are the initial amplitude of the vector potential on axis and the initial spot size of each beam. The parameter α is related to the curvature of the radiation wavefront and the parameter β is important in that it represents a correction to the parallel wave number on axis $k_\parallel = \omega/c + d\beta/dz$. This relation is used below to determine the beat wave phase velocity on axis.

Equations (3a) and (3b) describe the envelope evolution for each beam as it propagates through the plasma. Setting the right-hand sides of Eqs. (3a) and (3b) equal to zero gives

matched beam solutions for which the beams propagate without diffracting. Matched beam solutions are obtained for values of R in the range $1/(\sqrt{8}-1) < R < \sqrt{8}-1$ provided the normalized power W of each beam is given by

$$W_1 = [8R^2(1+R)^2 - (1+R)^4][64R^2 - (1+R)^4]^{-1}, \tag{5a}$$

$$W_2 = [8(1+R)^2 - (1+R)^4][64R^2 - (1+R)^4]^{-1}. \tag{5b}$$

This is illustrated in the following limits: For $R = 1$, then $W_1 = W_2 = 1/3$. As $R \to 1/(\sqrt{8}-1)$, then $W_1 \to 0$ and $W_2 \to 1$. As $R \to \sqrt{8}-1$, then $W_1 \to 1$ and $W_2 \to 0$. Hence, it is possible for a beam close to the critical power to confine a second beam which has a smaller spot size and a smaller power.

Matched beam propagation occurs when R, W_1 and W_2 are specified as indicated above. For example, once R is chosen in the range $1/(\sqrt{8}-1) < R < \sqrt{8}-1$, then W_1 and W_2 are given by Eqs. (5a) and (5b). The actual magnitudes of the spot sizes r_{s1} and r_{s2} are undetermined and only their ratio has been specified. Specifying a value for r_{s1} gives a value for the radiation beat wave phase velocity on axis according to the relation $c/v_p = 1 + c\Delta\beta'/\Delta\omega$, where $\Delta\beta' = d\beta_1/dz - d\beta_2/dz$. Alternatively, requiring $v_p = c$ for a given set of matched beam parameters R, W_1 and W_2 specifies r_{s1}. For example, as $R \to \sqrt{8}-1$, requiring $v_p = c$ gives $k_p^2 r_{s1}^2 \simeq 5\omega_1/\Delta\omega$, where $k_p = \omega_p/c$. For $R = 1$, requiring $v_p = c$ gives $k_p^2 r_{s1}^2 \simeq 2$. As $R \to 1/(\sqrt{8}-1)$, it is not possible to have $v_p = c$. For applications in the PBWA, it may be desirable to have $k_p^2 r_{s1}^2 >> 1$. This implies that it may be desirable to choose a matched beam case with $R > 1$. For example, $R = 1.5$ gives $W_1 \simeq 0.7$, $W_2 \simeq 0.1$ and $k_p^2 r_{s1}^2 \simeq 2.6\omega_1/\Delta\omega$.

As a final illustration, the above results are applied to parameters similar to those in the UCLA beat wave excitation experiment,[18] where $\omega_1 \simeq 2.0 \times 10^{14}$ sec^{-1} and $\Delta\omega/\omega_1 \simeq 9.7 \times 10^{-2}$ (which implies $n_p \simeq 10^{17}$ cm^{-3}). A test electron with intial energy given by $\gamma_0 = 50$ is accelerated by plasma waves generated in the following two special cases: i) A matched beam case with the beat wave phase velocity tuned to the speed of light, $v_p = c$, where $R = 1.5$, $r_{s1} = 8.3 \times 10^{-3}$ cm, $P_1 = 1.3 \times 10^{12}$ W and $P_2 = 1.6 \times 10^{11}$ W; and ii) the same parameters as case i) only now the beat wave phase velocity is given by the 1-D limit, $v_p/c \simeq 1 - \omega_p^2/2\omega_1^2$, and the radiation beams are assumed to undergo vacuum Rayleigh diffraction, $r_s = r_{s0}(1 + z^2/z_R^2)^{1/2}$. The results of case ii) are shown in Fig. 2 and the results of case i) are shown in Fig. 3. Figure 2 indicates that the test electron outruns the plasma wave and begins to be deaccelerated after approximately 0.5 cm with a maximum energy gain of $\Delta\gamma \simeq 210$. In Fig. 3, however, phase resonance between the

electron and beat wave is maintained which allows an energy gain of $\Delta\gamma \simeq 6500$ in 8 cm. This energy gain continues in a linear fashion until it becomes limited by some non-ideal effect such as pump depletion.[19]

Discussion

In summary, it has been shown that two colinear, short-pulse, Gaussian radiation beams can propagate through a uniform plasma without diffracting due to relativistic focusing. This occurs for values of R in the range $1/(\sqrt{8}-1) < R < \sqrt{8}-1$, provided W_1 and W_2 are specified according to Eqs. (5a) and (5b). In addition, it is possible to tune the phase velocity of the radiation beat wave to the speed of light for cases where $R \geq 1$. This is accomplished by appropriately choosing r_{s1}. In an actual PBWA, $\Delta\omega = \omega_p$ and the envelope behavior of the radiation beams becomes more complicated due to the presence of large amplitude resonantly driven plasma waves.[20] However, the analysis presented here remains valid for the front of the radiation pulse (the first several plasma wavelengths) where the amplitude of the plasma wave remains small. In the small amplitude limit, the phase velocity of the plasma wave is equal to that of the radiation beat wave.[21] Assuming that the phase velocity of the plasma wave remains fixed to its initial value, then the above analysis indicates that it is possible to tune this phase velocity to the speed of light. This implies that phase detuning between the plasma wave and the electrons can, in principle, be avoided which results in a substantially higher energy gain in the PBWA.

Acknowledgements

The authors would like to acknowledge useful discussions with C.-M. Tang. This work was supported by the U.S. Department of Energy.

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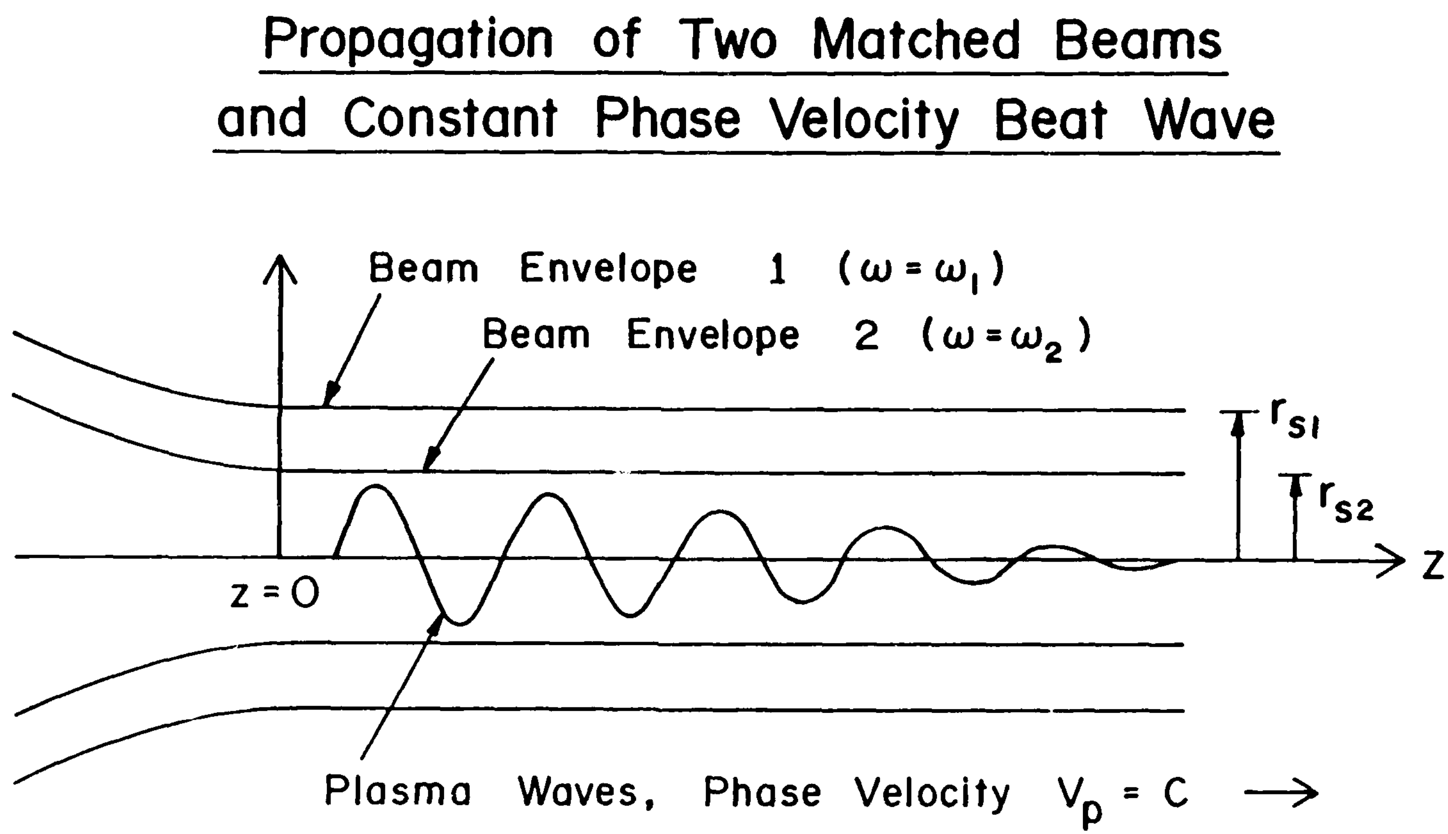

FIG. 1. Schematic of the PBWA for matched propagation of two radiation beams with constant spot sizes where the resulting beat wave phase velocity equals the speed of light.

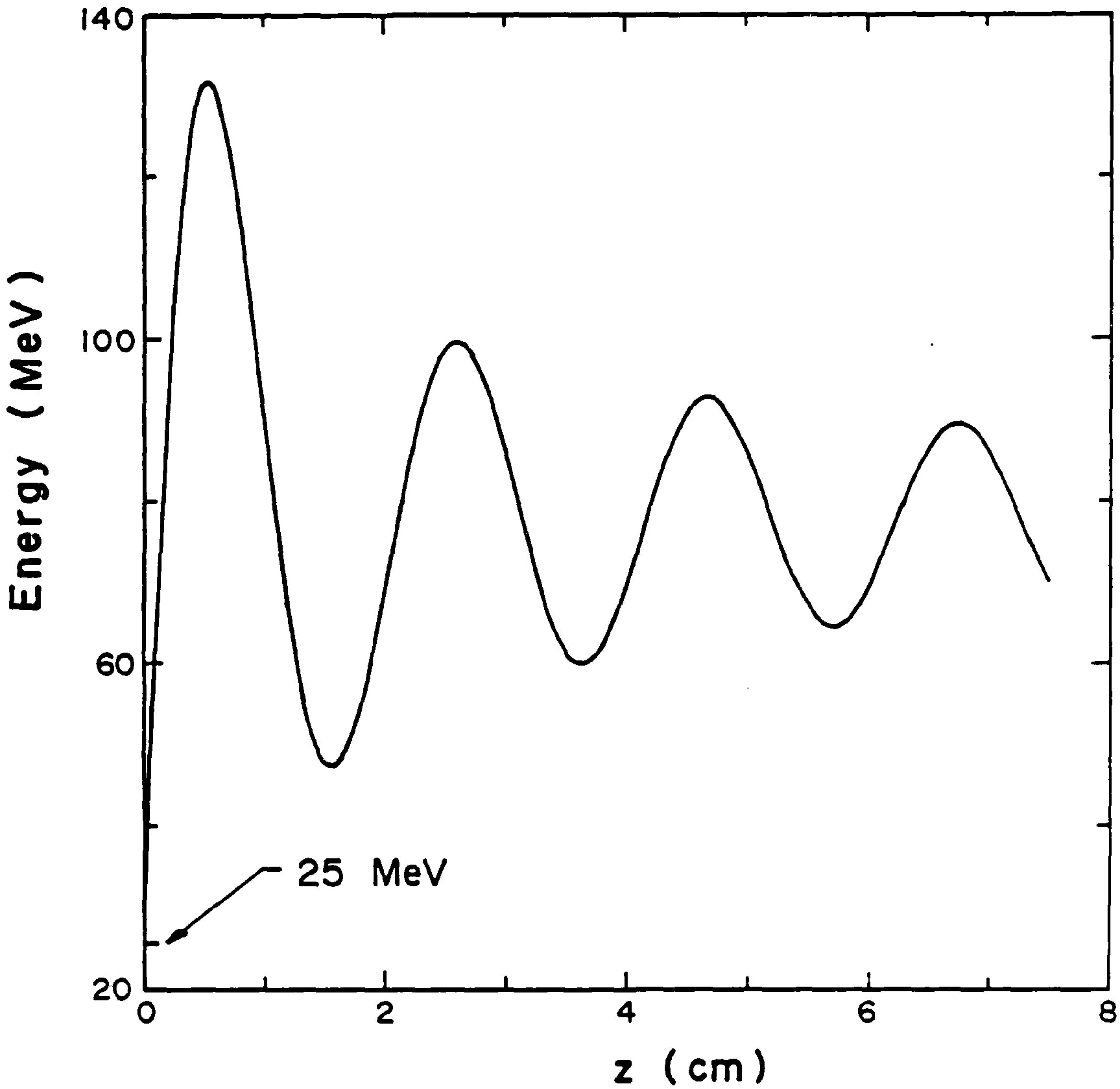

FIG. 2. Test electron acceleration with the same parameters as Fig. 3 except the phase velocity is given by the 1-D limit and the radiation beams undergo vacuum Rayleigh diffraction.

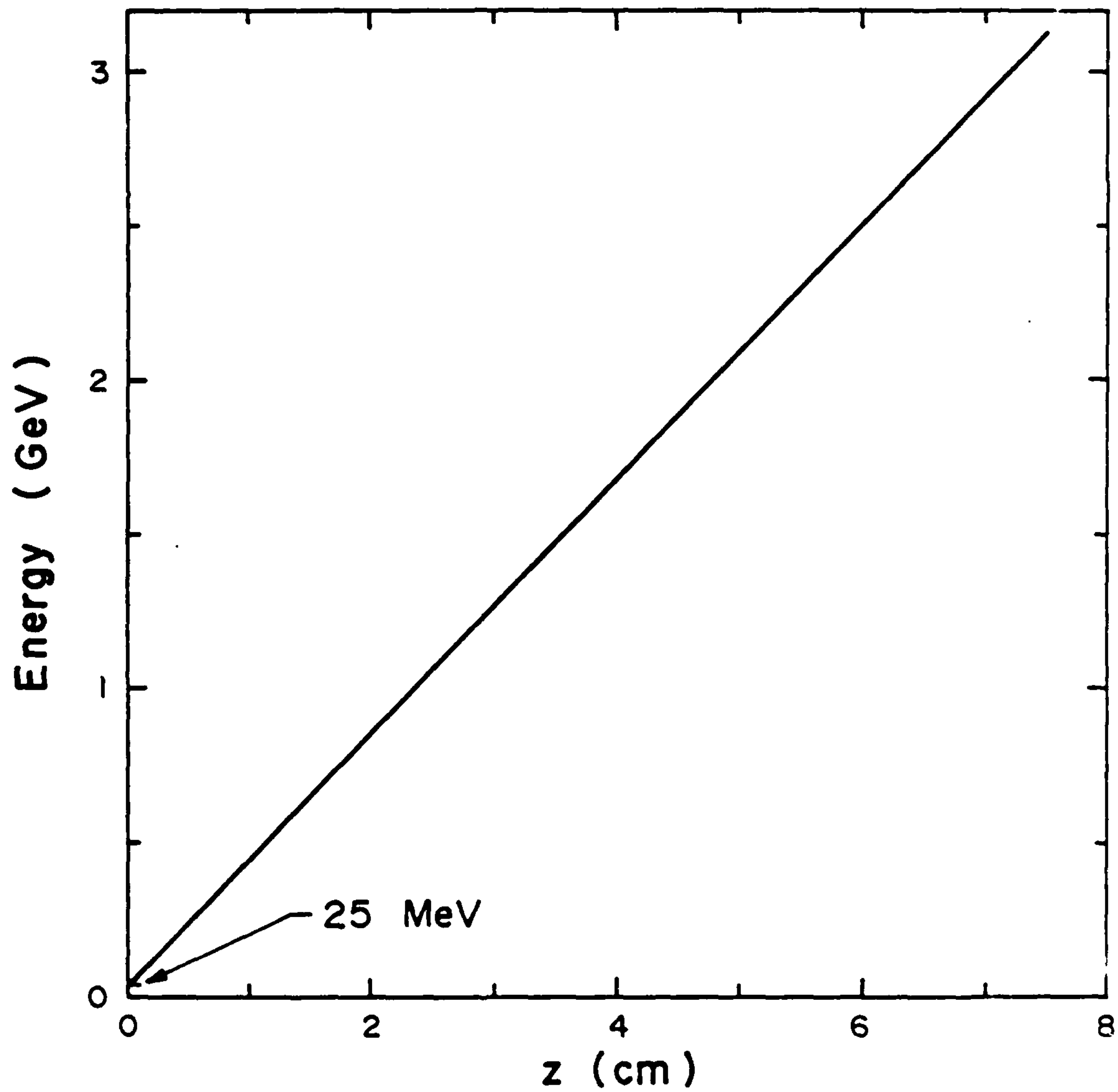

FIG. 3. Test electron acceleration for a matched beam case with $v_p = c$, where $R = 1.5$, $r_{s1} = 8.3 \times 10^{-3}$ cm, $P_1 = 1.3 \times 10^{12}$ W and $P_2 = 1.6 \times 10^{11}$ W.

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UCLA, 7731 Boelter Hall
Electrical Engineering Dept.
Los Angeles, CA 90024

Dr. K. Wendell Chen
Center for Accel. Tech.
University of Texas
P.O. Box 19363
Arlington, TX 76019

Dr. Pisin Chen
SLAC, Bin 26
P.O. Box 4349
Stanford, CA 94305

Dr. Marvin Chodorow
Stanford University
Dept. of Applied Physics
Stanford, CA 94305

Major Bart Clare
USASDC
P. O. Box 15280
Arlington, VA 22215-0500

Dr. Christopher Clayton
UCLA, 1538 Boelter Hall
Electrical Engineering Dept.
Los Angeles, CA 90024

Dr. Bruce I. Cohen
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. B. Cohn
L-630
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. B. Cole
Univ. of Wisconsin
Madison, WI 53706

Dr. Francis T. Cole
Fermi National Accelerator Laboratory
Physics Section
P. O. Box 500
Batavia, IL 60510

Dr. Richard Cooper
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Ernest D. Courant
Brookhaven National Laboratory
Upton, NY 11973

Dr. Paul L. Csonka
Institute of Theoretical Sciences
and Department of Physics
University of Oregon
Eugene, Oregon 97403

Dr. Chris Darrow
UCLA
1-130 Knudsen Hall
Los Angeles, CA 90024

Dr. J. M. Dawson
Department of Physics
University of California, Los Angeles
Los Angeles, CA 90024

Dr. Adam Drobot
Science Applications Intl. Corp.
1710 Goodridge Dr.
Mail Stop G-8-1
McLean, VA 22102

Dr. D. F. DuBois, T-DOT
Los Alamos National Laboratory
Los Alamos, NM 87545

Dr. J. J. Ewing
Spectra Technology
2755 Northup Way
Bellevue, WA 98004

Dr. Frank S. Felber
11011 Torreyana Road
San Diego, CA 92121

Dr. Richard C. Fernow
Brookhaven National Laboratory
Upton, NY 11973

Dr. H. Figueroa
1-130 Knudsen Hall
U. C. L. A.
Los Angeles, CA 90024

Dr. Jorge Fontana
Elec. and Computer Eng. Dept.
Univ. of Calif. at Santa Barbara
Santa Barbara, CA 93106

Dr. David Forslund
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. P. Garabedian
Courant Inst. of Math. Sciences
New York University
New York, NY 10012

Dr. Walter Gekelman
UCLA - Dept. of Physics
1-130 Knudsen Hall
Los Angeles, CA 90024

Dr. Dennis Gill
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. B. B. Godfrey
Mission Research Corporation
1720 Randolph Road, SE
Albuquerque, NM 87106

Dr. P. Goldston
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Prof. Louis Hand
Dept. of Physics
Cornell University
Ithaca, NY 14853

Dr. J. Hays
TRW
One Space Park
Redondo Beach, CA 90278

Dr. Wendell Horton
University of Texas
Physics Dept., RLM 11.320
Austin, TX 78712

Dr. J. Y. Hsu
General Atomic
San Diego, CA 92138

Dr. H. Huey
Varian Associates
B-118
611 Hansen Way
Palo Alto, CA 95014

Dr. Robert A. Jameson
Los Alamos National Laboratory
AT-Division, MS H811
P.O. Box 1663
Los Alamos, NM 87545

Dr. G. L. Johnston
NW16-232
M. I. T.
Cambridge, MA 02139

Dr. Shayne Johnston
Physics Department
Jackson State University
Jackson, MS 39217

Dr. Mike Jones
MS B259
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. C. Joshi
7620 Boelter Hall
Electrical Engineering Department
University of California, Los Angeles
Los Angeles, CA 90024

Dr. E. L. Kane
Science Applications Intl. Corp.
McLean, VA 22102

Dr. Tom Katsouleas
UCLA, 1-130 Knudsen Hall
Department of Physics
Los Angeles, CA 90024

Dr. Rhon Keinigs MS-259
Los Alamos National Labortory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Kwang-Je Kim
Lawrence Berkeley Laboratory
University of California, Berkeley
Berkeley, CA 94720

Dr. S. H. Kim
Center for Accelerator Technology
University of Texas
P.O. Box 19363
Arlington, TX 76019

Dr. Joe Kindel
Los Alamos National Laboratory
P. O. Box 1663, MS E531
Los Alamos, NM 87545

Dr. Ed Knapp
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Peter Kneisel
Cornell University
F. R. Newman Lab. of Nucl. Studies
Ithaca, NY 14853

Dr. Norman M. Kroll
University of California, San Diego
San Diego, CA 92093

Dr. Michael Lavan
Commander, U. S. Army
Strategic Defense Command
Attn: CSSD-H-D
P. O. Box 1500
Huntsville, AL 35807-3801

Dr. Kenneth Lee
Los Alamos National Laboratory
P.O. Box 1663, MS E531
Los Alamos, NM 87545

Dr. Baruch Levush
Dept. of Physics & Astronomy
University of Maryland
College Park, MD 20742

Dr. Chuan S. Liu
Dept. of Physics & Astronomy
University of Maryland
College Park, MD 20742

Dr. N. C. Luhmann, Jr.
7702 Boelter Hall
U. C. L. A.
Los Angeles, CA 90024

Dr. Clare Max
Institute of Geophysics
& Planetary Physics
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. B. D. McDaniel
Cornell University
Ithaca, NY 14853

Dr. Colin McKinstrie
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Prof. Kim Molvig
Plasma Fusion Center
Room NW16-240
M.I.T.
Cambridge, MA 02139

Dr. A. Mondelli
Science Applications Intl. Corp.
1710 Goodridge Drive
McLean, VA 22101

Dr. Warren Mori
1-130 Knudsen Hall
U. C. L. A.
Los Angeles, CA 90024

Dr. P. L. Morton
Stanford Linear Accelerator Center
P. O. Box 4349
Stanford, CA 94305

Dr. John A. Nation
Laboratory of Plasma Studies
369 Upson Hall
Cornell University
Ithaca, NY 14853

Dr. K. C. Ng
Courant Inst. of Math. Sciences
New York University
New York, NY 10012

Dr. Robert J. Noble
S.L.A.C., Bin 26
Stanford University
P.O. Box 4349
Stanford, CA 94305

Dr. J. Norem
Argonne National Laboratory
Argonne, IL 60439

Dr. Craig L. Olson
Sandia National Laboratories
Plasma Theory Division 1241
P.O. Box 5800
Albuquerque, NM 87185

Dr. H. Oona
MS-E554
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Robert B. Palmer
Brookhaven National Laboratory
Upton, NY 11973

Dr. Richard Pantell
Stanford University
308 McCullough Bldg.
Stanford, CA 94305

Dr. John Pasour
Mission Research Corporation
8560 Cinderbed Rd.
Suite 700
Newington, VA 22122

Dr. Samual Penner
Center for Radiation Research
National Bureau of Standards
Gaithersburg, MD 20899

Dr. Claudio Pellegrini
National Synchrotron Light Source
Brookhaven National Laboratory
Upton, NY 11973

Dr. Melvin A. Piestrup
Adelphi Technology
13800 Skyline Blvd. No. 2
Woodside, CA 94062

Dr. Z. Pietrzyk
FL-10
University of Washington
Seattle, WA 98185

Dr. Don Prosnitz
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. R. Ratowsky
Physics Department
University of California at Berkeley
Berkeley, CA 94720

Dr. Charles W. Roberson
Office of Naval Research
Detachment Arlington
800 North Quincy St., BCT # 1
Arlington, VA 22217-5000

Dr. Stephen Rockwood
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Harvey A. Rose, T-DOT
Los Alamos National Laboratory
Los Alamos, NM 87545

Dr. James B. Rosenzweig
Dept. of Physics
University of Wisconsin
Madison, WI 53706

Dr. Alessandro G. Ruggiero
Argonne National Laboratory
Argonne, IL 60439

Dr. R. D. Ruth
SLAC, Bin 26
P. O. Box 4349
Stanford, CA 94305

Dr. Jack Sandweiss
Gibbs Physics Laboratory
Yale University
260 Whitney Avenue
P. O. Box 6666
New Haven, CT 06511

Dr. Al Saxman
Los Alamos National Laboratory
P.O. Box 1663, MS E523
Los Alamos, NM 87545

Prof. John Scharer
Electrical & Computer Engineering Dept.
University of Wisconsin
Madison, WI 53706

Dr. George Schmidt
Stevens Institute of Technology
Department of Physics
Hoboken, NJ 07030

Dr. N. C. Schoen
TRW
One Space Park
Redondo Beach, CA 90278

Dr. Frank Selph
U. S. Department of Energy
Division of High Energy Physics, ER-224
Washington, DC 20545

Dr. Andrew M. Sessler
Lawrence Berkeley Laboratory
University of California, Berkeley
Berkeley, CA 94720

Dr. Richard L. Sheffield
Los Alamos National Laboratory
P.O. Box 1663, MS H825
Los Alamos, NM 87545

Dr. John Siambis
Lockheed Palo Alto Research Laboratory
3251 Hanover Street
Palo Alto, CA 94304

Dr. Robert Siemann
Dept. of Physics
Cornell University
Ithaca, NY 14853

Dr. J. D. Simpson
Argonne National Laboratory
Argonne, IL 60439

Dr. Charles K. Sinclair
Stanford University
P. O. Box 4349
Stanford, CA 94305

Dr. Sidney Singer
MS-E530
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. R. Siusher
AT&T Bell Laboratories
Murray Hill, NJ 07974

Dr. Jack Slater
Mathematical Sciences, NW
2755 Northup Way
Bellevue, WA 98009

Dr. Todd Smith
Hansen Laboratory
Stanford University
Stanford, CA 94305

Dr. Richard Spitzer
Stanford Linear Accelerator Center
P. O. Box 4347
Stanford, CA 94305

Mr. J. J. Su
UCLA
1-130 Knudsen Hall
Los Angeles, CA 90024

Prof. Ravi Sudan
Electrical Engineering Department
Cornell University
Ithaca, NY 14853

Dr. Don J. Sullivan
Mission Research Corporation
1720 Randolph Road, SE
Albuquerque, NM 87106

Dr. David F. Sutter
U. S. Department of Energy
Division of High Energy Physics, ER-224
Washington, DC 20545

Dr. T. Tajima
Department of Physics
and Institute for Fusion Studies
University of Texas
Austin, TX 78712

Dr. Lee Teng, Chairman
Fermilab
P.O. Box 500
Batavis, IL 60510

Dr. H. S. Uhm
Naval Surface Warfare Center
White Oak Laboratory
Silver Spring, MD 20903-5000

U. S. Naval Academy (2 copies)
Director of Research
Annapolis, MD 21402

Dr. William A. Wallenmeyer
U. S. Dept. of Energy
High Energy Physics Div., ER-22
Washington, DC 20545

Dr. John E. Walsh
Department of Physics
Dartmouth College
Hanover, NH 03755

Dr. Tom Wangler
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. S. Wilks
Physics Dept.
1-130 Knudsen Hall
UCLA
Los Angles, CA 90024

Dr. Perry B. Wilson
Stanford Linear Accelerator Center
Stanford University
P.O. Box 4349
Stanford, CA 94305

Dr. W. Woo
Applied Science Department
University of California at Davis
Davis, CA 95616

Dr. Jonathan Wurtele
M.I.T.
NW 16-234
Plasma Fusion Center
Cambridge, MA 02139

Dr. Yi-Ton Yan
Los Alamos National Laboratory
MS-K764
Los Alamos, NM 87545

Dr. M. Yates
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Ken Yoshioka
Laboratory for Plasma and Fusion
University of Maryland
College Park, MD 20742

Dr. R. W. Ziolkowski, L-156
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550